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more mobile with the Lower Carboniferous and especially during the Jurassic and Cretaceous. During this very long time, the eastern half of the continent, a land about 1800 miles east and west and 2200 miles north and south, nearly all went down more and more beneath the level of the sea to a maximum depth of about four miles and an average depth of between one and two and a half miles. Further, the entire area of the Oceanides also subsided, and possibly to an equally great depth; while this was taking place the bottom was apparently folded and built up by volcanic material into many more or less parallel ridges, a series of arcs extending over an area of about 3500 miles east and west and the same distance north and south. Finally, we may add that the entire western half of the Pacific bottom appears to be as mobile as any of the continents of the northern hemisphere, with the difference that the sum of the continental movements is upward, while that of the ocean bottoms is downward. This paper will be published at greater length and with illustrations in the *American Journal of Science*.

<sup>1</sup> Suess, *Natural Science*, 2, 180 (1893).

<sup>2</sup> Park, *Geology of New Zealand*, 1910.

<sup>3</sup> Süssmilch, *Geology of New South Wales*, 1911.

## THE PETROLOGY OF SOME SOUTH PACIFIC ISLANDS AND ITS SIGNIFICANCE

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Petrology as a more comprehensive term than petrography embraces all the phenomena and material characters of rocks, as well as the theories regarding their origin and the relations between the rocks of the earth and the problems of geodynamics. Knowledge of the composition, mode of occurrence, and distribution of igneous rocks should contribute materially to the elucidation of those problems in geology which are concerned with the constitution and behavior of the outer and inner portions of the earth.

For many years some geologists and petrologists have been convinced that the various kinds of igneous rocks in different parts of the world, both volcanic outflows and intruded bodies, are so intimately related to one another within each region that they must have been derived from some parent lava, or rock magma, by processes of physico-chemical differentiation; and further, that in different regions of the earth the series of igneous rocks in each possess chemical and mineral

characteristics which distinguish them from series of rocks in other regions. In short, that the series of igneous rocks in various parts of the world are not exactly alike, though some may be.

Recently I have called attention to the apparent relation between regional characteristics of igneous rocks and the broad demands of the theory of isostasy. The igneous rocks of the North American continent, both as a whole and when considered in regional groups, such as those of the Pacific cordilleras, the Colorado plateau, or the Atlantic coast, average lighter than the igneous rocks of islands in the deep oceans such as Hawaii in the Pacific, and Réunion in the Indian Ocean. The relative densities of a completely crystallized average magma of the Pacific Coast rocks, and those of average magmas for Hawaii and Réunion are to one another as 2.85 to 3.12, for each of the island groups of rocks. This appears to be in accord with the demands of isostasy, if igneous rocks represent the material forming deep portions of the lithosphere, or material immediately below it, or at its base. However, much remains to be done in studying the igneous rocks of all parts of the earth, especially of the little known islands of the Pacific Ocean.

It was with the hope of contributing something to the solution of the problem of isostasy from the petrographic side that I undertook recently a reconnaissance of some volcanic islands in the South Pacific, namely: Tahiti, Moorea, the Leeward Islands: Huahine, Raiatea, Tahaa and Bora Bora; besides the two largest islands of the Marquesas, Hiva-oa and Nukahiva.

So long ago as 1849 James D. Dana published an excellent description of Tahiti, and mentioned the occurrence of a variety of syenite among the basalts of this volcano, which he considered to be "only a feldspathic variety of the same igneous rocks that constitute the island;" a perfectly correct assumption. Darwin visited Tahiti a few years earlier than Dana and noted the basaltic character of the rocks. In a conversation with the writer 30 years ago Dana remarked "If you want to study a dissected volcano, go to Tahiti." At that time it seemed a difficult thing to do. Today the island is on a direct mail route between San Francisco and Wellington, N. Z.

In 1910 Lacroix published a description of Tahitian rocks which were in the Museum of National History in Paris. Besides abundant basalts the collection embraced coarsely crystallized gabbros, syenites and lavas that are characterized by nephelite and haüynite, minerals generally considered absent from igneous rocks occurring in the region of the Pacific Ocean, but already found to some extent in the Hawaiian and Samoan Islands.

Professor Marshall, of Dunedin, N. Z., has described nephelite-bearing rocks from the Cook Islands and from some of the Leeward Islands in the Society group; and in 1915 he published an account of his journey to the center of the island of Tahiti. From these descriptions it was known that all of these islands are basaltic and that some of them contain trachytes and phonolites, but the relative abundance of these rocks and the more specific characters of the basaltic lavas were not definitely known, and no approach to an estimate of the average magmas of the several islands could be gained from the fragmentary nature of the information at hand.

A reconnaissance of the islands was thought to be worth the effort, and has been productive of valuable results. However, a great deal remains to be done in the way of more accurate detail exploration of the islands than I was able to carry on in the few months at my disposal, and with the limited means at my command.

Tahiti, the largest island in this region, is an extinct volcano, deeply eroded by streams that have cut canyon-like valleys, which radiate from a circular range of high mountains, surrounding the deep central basin heading Papenoo valley, which drains northward. This central basin is 5 or 6 miles across from crests of the encircling range with its peaks of 4000, 5000, 6000, and in Orofena of 7000 feet in altitude.

In the geometrical center of the island, which is in the western head of the Papenoo Valley, there is a low conical hill, Ahititera, composed of coarsely crystallized rocks, gabbros, peridotites with subordinate amounts of nephelite-syenite and other rocks. The surrounding rocks, so far as seen through the forest of tropical vegetation, are basaltic tuff breccias and basaltic lava flows, the latter preponderating in the upper parts of the mountains and in the outlying spurs and slopes of the ancient volcano.

The top of the central hill, Ahititera, is about 2500 feet above sea level, and may be assumed to be about 7000 feet below what was at one time the bottom of the final crater of the volcano, if the mountain had the same profile as the great modern volcanoes of Hawaii. The valley bottoms are nearly level for miles inland from the coast, and their heads lie deep below the summits of the mountain ridges between them. Their sides are very steep, in many places almost vertical walls, thinly covered with clinging ferns and vines.

The lavas composing the Tahitian volcano are basalts rich in ferromagnesian minerals, which commonly appear as prominent crystals. Feldspars are seldom seen, but are prominent in some varieties of the basaltic lavas. There are very few lavas with a trachytic appearance

on the main island of Tahiti, though they are common on the lesser volcano of Taiarapu which is connected with Tahiti by a narrow isthmus.

The preponderating lavas of the Taiarapu volcano are basalts like those of Tahiti proper. The smaller volcano has been deeply eroded, and a central valley reveals a core of coarse-grained rocks: gabbros and peridotites, which represent the lavas that solidified in the conduit of this volcano when it became extinct. No syenites were found among the rocks, although trachytes and phonolites are common among the latest lavas in the upper, or marginal, parts of this volcano. Such alkalic feldspathic lavas are clearly differentiates of the basaltic magma, the complimentary varieties being peridotites and peridotitic lavas which are characteristic of these and neighboring volcanoes.

Of the chemical analyses of Tahitian rocks already published by Lacroix two are of preponderating varieties of basalt, and two are of preponderating varieties of gabbro from the central core in Papenoo Valley. The four analyses agree closely with one another and their average may be considered a first approximation to what was probably the parent magma from which all the lavas of Tahiti were derived. The estimated specific gravity of a completely crystallized rock of such a composition is 3.18. The average of the relative densities of 4 specimens of gabbros and peridotites from the Papenoo Valley is 3.18, and of 4 similar rocks from the central valley of Taiarapu is 3.16. These estimates leave out of account the syenites, trachytes and phonolites of the island, for the amount of these rocks when compared with the bulk of the basaltic volcanoes is almost negligible.

This preliminary estimate of the relative density of the solidified magmas of these two volcanoes may be slightly too high, and is somewhat greater than those calculated for the solidified magmas of Hawaii and Réunion. It clearly indicates that the magma from which the Tahitian volcanoes sprang is sufficiently heavy to correspond to the great depth of the Pacific Ocean in this region according to the theory of isostasy.

Moorea, or Eimeo, is an island volcano ten miles northwest of Tahiti, which has been greatly eroded and partly submerged under the sea. The central portion has been reduced to a deep valley surrounded by high precipitous mountains 2500 to 3500 feet in height. The upper portions are composed of horizontal layers of basalt lava. The central basin is drained northward by two valleys, drowned by the sea, forming bays with a high mountain ridge between. Small, radial, valleys cut the main ridge into short spurs which pitch steeply to the coast. The exposed lava sheets are seen to dip away from the center of the

island toward the ocean, and show that the volcano originally was a flat-topped dome, the upper portion of which was mostly solid flows of lava, while the lower middle part of the volcano was largely tuffs and breccia.

No core, or conduit, of coarsely crystallized rocks has been exposed by erosion, which is an indication that the volcano of Moorea was not as high above the sea as those of Tahiti and Taïarapu. The deep bays in Moorea show that this volcano has been flooded by the sea to a considerable depth, while the absence of bays on Tahiti indicates that this island and Taïarapu have not sunken sufficiently to submerge the deeply eroded valleys, although the lower portions of the stream channels are only a few feet above the surface of the sea. The principal lavas of Moorea are basalts like those of Tahiti, but there are subordinate though large bodies of trachytic and phonolitic lavas, and small bodies of peridotitic rocks.

The Leeward Islands, or the Society Group, 100 miles northwest of Tahiti, are similar in structure and in the character of their lavas. Huahine, the most easterly, is a volcano so greatly eroded and flooded that a narrow, shallow, strait separates the northern from the southern portion, and connects the heads of east and west bays. The eroded center of the volcano is submerged in the head of the east bay. The mountains and ridges, with spurs sloping seaward, consist of lava flows nearly horizontal in the central peaks, but dipping down the spurs and ridges in all directions toward the coast. The basaltic lavas have the same general composition as those of Tahiti, but there are mountain masses of phonolite and trachyte in several parts of the island.

Raiatea, the largest island of this group, consists of basaltic breccias at its center, with basaltic lavas in sheets which are horizontal in the upper parts of the central mountains, but slope toward the coast in the spurs. A great sheet of trachytic lava caps the long ridge forming the middle of the northern portion of the island, and reaches the shore at the ends of the northwest spurs. There are also several mountain masses of phonolite. The volcanic center of the island has been eroded to a deep valley draining east and flooded by the sea. There are several other drowned valleys on Raiatea.

Tahaa, which is within the same lagoon and barrier reef as those surrounding Raiatea, is another dissected volcano having a deeply indented coast with bays extending to some distance inland, and having lava flows dipping down the spurs to the sea, and more or less horizontal in the central portion.

Farther west, the smaller island, Bora Bora, is much more reduced

by erosion, and consists of a central mountain about 2500 feet in height, with a vertical escarpment of fully a thousand feet which exposes horizontal basaltic lavas. The marginal ridges surrounding two deep bays are the remnants of volcanic slopes in which the lava sheets dip outward toward the surrounding lagoon.

The still smaller island of Maupiti is the remains of a basaltic volcano almost completely submerged in the ocean. The encircling lagoon is relatively larger than those about the less submerged islands farther east. In fact there is a progressive relation between the width and depth of the lagoons around these islands and the apparent submergence of the volcanoes. The most deeply submerged islands and relatively largest lagoons are in the west or northwest, that is, in the Leeward islands, and in the northwestern part of these.

There is less submergence and the lagoons are less well developed at Moorea and Tahiti. However, in this, the Georgian group, Tetiaroa, 26 miles north of Tahiti, is only an atoll, while Mehetia, 60 miles east of Tairapu is said to be an extinct crater 435 meters high, having a peak to the north and a gentle slope to the south, and having a difficult coast.

The islands of the Marquesan group, 600 miles northeast of Tahiti, are extinct and eroded volcanoes consisting of heavy basalts similar to those of Tahiti and the Leeward Islands, with quite subordinate amounts of trachytic lavas. Erosion has cut deeply into the volcanic mountains in places and has carved steeply walled valleys, surrounded by precipitous mountain ridges, with some commanding peaks, as at Traitors Bay and the Bay of Hanaiapa on Hiva-*oa*, and along the south coast of Nukahiva. This coast is very rugged with cliffs 1000 feet high, topped by hanging valleys.

The coasts of Nukahiva and of Hiva-*oa* plunge steeply into the sea which in places is a thousand feet deep within a few hundred feet from shore. No coral reefs surround these islands, though a few fragments of corals are found on the beaches which occur at intervals along the coast. Small reefs of coral are said to occur in some localities in this region. The northwestern side of Nukahiva is a long, gentle volcanic slope reaching sea level.

In the Marquesan Islands, so far as my observations go, sea erosion appears to have progressed more rapidly than stream erosion in places where sea cliffs rise to great heights, with hanging valleys and with waterfalls plunging into the sea. However, there are great differences in the topographic relief in neighboring parts of the same island, as on Hiva-*oa*, where in the western portion deep valleys have been cut with

mountainous walls and sharply serrated dividing ridges, while in the middle portion of the island there are broad expanses of rolling highlands which are drained by shallow channels, or short steep gulches.

The high massive cliffs along parts of the coasts and around some of the largest valleys are probably due to the fact that the upper thousand feet of the ancient volcanoes consisted of superimposed sheets of dense lava, beneath which are breccias and tuffs which yield much more readily to erosion and permit the overlying massive portions to be undermined. From the great depth of the sea off the coast and within the bays, as well as from the absence of coral reefs or of extensive sea shelves, it appears probable that these islands have been submerged to a considerable depth within comparatively recent times.

## IN RELATION TO THE EXTENT OF KNOWLEDGE CONCERNING THE OCEANOGRAPHY OF THE PACIFIC

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The body of water whose oceanography is under discussion is of an extent so vast that its area exceeds by 10,000,000 square miles the total land surface of the globe, and its cubical content is estimated to be seven-fold greater than all the land above sea-level. The indications are that throughout nine-tenths of its expanse the depths are greater than one mile, and throughout three-fourths of its expanse the depths are greater than two miles. It is the field of the interplay of many different forces exercising an important influence in terrestrial physics, and presents a realm of unsurpassed promise for the fruits of investigation.

The accumulated oceanographical observations in the Pacific relate principally to the surface and the bottom. Even these are deficient, and the intermediate depths have been much less investigated. The materials from centuries of voyaging and from the expeditions for sounding the ocean sent forth since the last quarter of the nineteenth century, when deep-sea soundings first began to be taken in the Pacific, have provided information of the general distribution of barometric pressure and winds over this vast tract and also of the general aspects of surface circulation, temperature, and salinity; but the details of these matters have scarcely been touched. Until the tides have been gauged in the open ocean away from the land, it is not likely that a clear solution of the tidal problem will be completed. Despite the